

HIGH STRENGTH CONCRETE FOR SUSTAINABLE CONSTRUCTION

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Abstract: The use of HSC for construction, especially for multi-story buildings, has become very common in industrialized and developing countries. In view of gaining popularity as a construction material, high strength concrete (HSC) properties are discussed in this paper. A brief review of literature is presented. The necessary ingredients of HSC such as fly ash, slag and silica fume which are mostly industrial byproducts make the product environmentally friendly. The main engineering properties of the HSC are also reviewed.

Keywords: High Strength Concrete, Engineering Properties, Environment

1. Introduction

During the past few years, high-strength concrete (HSC) has been generating increased interest amongst civil and structural engineers. The expanding commercial use of this relatively new construction material can be explained partially by the life cycle cost-performance ratio it offers, as well as its outstanding engineering properties, such as higher compressive and tensile strengths, higher stiffness and better durability, when compared to the conventional normal strength concrete (NSC). From a historical point of view, in the middle of the 20th century concrete with characteristic strength (f'_c) of 25MPa was considered high-strength. In the 1980s, 50MPa concrete was considered high-strength. About two decades ago, HSC was mostly specified for projects as an alternate design. But today, HSC is being specified in the preliminary design stage as a sensible solution for concrete construction. Nowadays, technology for producing HSC has sufficiently advanced such that concretes with compressive strengths of up to about 120MPa are commercially available, and strengths much higher than that can be produced in the laboratories. The significant economic advantages of HSC are very well-documented, and evident from the number of recent construction projects where HSC has been used successfully [1].

The use of HSC for construction, especially for multi-story buildings, has become very common in industrialized and developing countries. In Australia, where the majority of buildings are concrete structures, almost all concrete high-rise and medium-rise building projects utilize HSC. Australia has taken the advantage of the benefits of high-strength concrete [2, 3] through its widespread use on buildings such as 120 Collins Street, Melbourne Central, the Rialto project in Melbourne, the 43-storey high Casselden Place project in Melbourne. In Seattle USA, the strength of concrete used on the Pacific First Centre was about 125MPa [4]. The Freedom Tower in New York City, which will be one of the world's tallest superstructures, is projected to be completed in 2010. The structure consists of a robust high-strength concrete core paired with a highly redundant perimeter steel moment resisting frame. Most experience on HSC in Europe has been gathered in Norway, with that country's development in offshore platforms, bridges, and highway pavements [5]. In Germany, HSC was first utilized in a high-rise building in Frankfurt, completed in 1992. HSC with a mean strength of 100 MPa was used in the Petronas Towers in Kuala Lumpur in 1998. The Eureka Tower, which is one of the tallest buildings in Australia was completed in 2006 has utilized HSC up to 100 MPa.

In general, concrete is not considered as a sustainable construction material in terms of large consumption of raw materials, contribution to greenhouse gas emissions from cement and low durability. The ruling argument is that the production of 1kg of cement which, is the main ingredient of concrete, generates 0.8 - 0.9kg of CO₂ emission [6]. It is commonly argued that with a high growth rate, the demand for concrete consumption will substantially increase in the near future imposing a heavy burden on the ecological system. The CO₂ emission related to concrete production, inclusive of cement production is between 0.1 and 0.2tonne per 1tonne of produced concrete [7]. The

environmental impact of concrete as a construction product is questionable with studies demonstrating concrete products requiring much less energy with a lower net environmental impact when compared to other construction materials such as steel [8]. Regardless of the impact to the environment, it is a true fact that currently urbanization worldwide relies heavily on the concrete industry. Worldwide, some 6 billion tons of concrete is produced per year, making concrete one of the world's most popular construction materials. On the economical front, this represents about 13 to 14 trillion USD world trade dealing [9].

In view of the importance of climate change, sustainability has become the main concern for the concrete industry. In order to assess the environmental impact of concrete, a multi-dimensional, life-cycle approach is adopted [9, 10]. The findings show that, when considering the life-cycle stages of the product into consideration in order to carry a comprehensive and impartial assessment, concrete can be considered as a material that burdens the environment least [11]. It is further reported that using high performance concrete has multiple environmental benefits. For instance, it is possible to build a durable structure with minimum maintenance that lead to a reduction in the consumption of raw materials and greenhouse gas emissions, and reclaiming industrial waste products and using them as effective construction materials [11].

In spite of this, steps have been taken in place to reduce the CO₂ emissions into the atmosphere. In order to limit the usage of Portland cement, the concrete industry has been increasingly inclined towards substituting Portland cement with fly ash, slag and micro silica fume all which are industrial byproducts. It is believed that this substitution can be increased without impairing the performance of the concrete grades [10].

This paper presents literature review of current studies undertaken on HSC. The review is divided into two parts. In the first part, the main constituents of HSC are presented. The main ingredients which influence the performance of HSC are discussed (Section 2). The addition of mineral admixtures which are mostly industrial by-products is common in the production of HSC. The effects of these admixtures on the concrete properties are also discussed. On the second part, the engineering properties of HSC concrete are presented (Section 3). For the purposes of this paper, HSC is defined as concrete with compressive strength, f'_c , in the range of 50 - 100 MPa. NSC is concrete with $f'_c < 50$ MPa.

2. High strength concrete constituents

The sustainable high performance concrete does not contain any special or unusual ingredients. A common mix includes Portland cement, super plasticizers, silica fume, fly ash and slag, with relatively large amount of cementitious by-products for cement replacement. The significance of each material in producing high strength concrete is discussed in this section.

2.1. Water/binder (w/b) ratio and cement content

HSC usually contains one or two mineral additives which are used as partial replacement for cement. Therefore, the term water/cement (w/c) ratio used in reference to normal strength concrete (NSC) is replaced by w/b ratio, where the binder is the total weight of the cementitious materials (cement + additives). The minimum w/b ratio for full hydration of cement pastes is approximately 0.36 [12]. For NSC this limit is usually exceeded for workability requirements. However, in the case of HSC, complete hydration is not essential for full strength to be attained and therefore it can be made with w/b ratios less than 0.36. HSC's have been made with w/b ratios as low as 0.2. However, high dosages of superplasticizers are required to maintain workability [13]. Patnaikuni and Patnaik [12] suggests that a w/b ratio of 0.23 is an optimum value for maximum compressive strength of very high-strength concrete mixes.

The incorporation of mineral admixtures such as silica fume, fly ash, slag or rice-husk ash is common in production of HSC concrete. These cementations by-products facilitate the manufacture of high-strength concrete.

2.2. Mineral admixtures

Silica fume

Silica fume is a by-product of the manufacturing process of silicon and ferrosilicon alloys and is in a form of glass which is highly reactive. The small size of particles will accelerate the reactions with calcium hydroxide which enables silica fume to replace Portland cement for a small proportion. The major purpose of introducing silica fume to the concrete mix is to achieve high strength and durability. The presence of silica fume also enhances the effectiveness of superplasticizer, which consequently reduces w/b ratio required to achieve a certain level of workability [14]. Normally, 3 to 10% of silica fume is used for high performance concrete. Behnood & Ziaria [15] found that the silica fume has more pronounced effects on compressive strength than a decrease in w/b ratio. The optimal value for silica fume and w/b were estimated to be 6% and 0.35 respectively. In an experimental study, Ting et al. [16] concluded that about 10% replacement of cement by silica fume is the optimum dosage.

Fly ash

Fly ash is a by-product of the combustion of pulverised coal in thermal power plants. It is removed as a fine dust by mechanical extractors, electrostatic precipitators or fabric filters. Fly ash can be included into concrete either blended with cement or directly introduced as an additional cementitious material at the concrete mixing plant. Typical applications are in pumped or in superplasticised concretes, particularly where heat of hydration is considered to be a problem.

The introduction of fly ash has effects on many properties such as workability, hydration, strength development shrinkage, heat evolution and durability. The inclusion of fly ash in the concrete mix reduces the water content required to produce a certain level of workability. Experimental studies by Jiang and Malhotra [17] have found the reduction of water content can be as high as 20%, if high quality of fly ash were used.

Fly ash generally has adverse effects on concrete strength, especially at the early age. However, fly ash may have better performance when the w/b ratio is low. It has been demonstrated that at w/b=0.5, a 45% fly ash resulted in about 30% reduction in 28-days strength, but at w/b ratio=0.3, the reduction in strength is reduced to 17% [18]. So far, it is possible to add 50% or more fly ash to replace Portland Cement to achieve sustainable high strength concrete with less than 130 kg/m³ water content and 200kg/m³ cement content.

Slag

Slag is a by-product material obtained from pig iron in the blast furnace and is formed by the combination of earthy constituents of iron ore with limestone flux. The presence of slag develops the workability and strength of concrete. Generally, the dosage rate of slag is between 15% and 30% of the cementitious material [19]. In fresh concrete, slag tends to improve the workability of the concrete due to their angular shape and smooth surface texture. Consequently, the required amount of superplasticizer could also be reduced by increasing slag content [20]. It has been shown that the compressive strength of concrete increases with increasing amount of copper slag when superplasticizer is not applied [21].

2.3. Coarse Aggregates

As compared to NSC, the mineralogy and the crushing strength of coarse aggregates has a significant effect on the strength of a HSC mix. According to Setunge [22], higher strength aggregates do not necessarily produce higher-strength concretes. A more desirable property is the compatibility of the stiffness of the aggregates and the mortar. The ideal material will be crushed rock with low stiffness and high strength. It is generally observed that smaller aggregates are desirable to produce high strength concrete due to reduction in the water accumulating near the coarse aggregates and larger available surface area for bonding with cement matrix. For commercial applications, taking into

account the economy of production, workability and shrinkage and creep, well graded aggregates of 14-20mm size are recommended.

Aitcin [23], for the purposes of discussion divided high-strength concrete and very high-strength concrete into five categories and discussed the relative importance of various factors on the strength of concrete. The first three categories are summarized in Table 1.

Table 1: Categories of HSC [23]

Category	Strength	
Category I	50–75MPa	Manufactured using good quality, but generally used materials, existing production technology and w/b ratio of about 0.4. Mineral admixtures are not required. Superplasticizers may be used to achieve the required workability,
Category II	75–100MPa	High quality, generally used materials are required. Due to the very low w/b ratio of about 0.25 - 0.30, superplasticizers are required to achieve adequate workability. The use of mineral admixtures is also strongly recommended. The coarse aggregates must be round or cubic in shape.
Category III	100-125MPa	Very high quality materials, efficient mixing techniques and stringent quality control needed. The w/b ratio must be lowered to 0.22-0.25. High dosages of superplasticizers are essential in conjunction with silica fume.

The other two categories refer to 125 MPa and beyond and will not be discussed here as they are not commonly used and difficult to achieve in the field.

2.4. Superplasticizers

Superplasticizers are essential to produce good workable high-strength concrete. There are, basically three principal types of superplasticizers:

(i) lignosulfonate-based (ii) melamine sulfonate and (iii) naphthalene sulfonate.

In general, a combination of the above types is used for high-strength concrete. The amount of superplasticizer to be added to a mix is governed by the required workability.

2.5. Curing

De Larrad [25] reports that self-desiccation is probable in HSC and hence specimens cured in water will absorb water, thus increasing the strength of the concrete. An opposite view is expressed by some who argue that water evaporation from a NSC cylinder is greater than that from a HSC cylinder. Therefore, the strength development of a NSC cylinder will be more affected by deficient curing than the strength development of a HSC cylinder.

Studies by Aitcin [26] on curing of HSC show that HSC members have a delayed response to strength gain. Aitcin suggests that due to the low permeability of high-strength concrete it takes considerable time for water to penetrate the concrete and contribute to the hydration process, hence longer periods of moist curing of HSC specimens is recommended.

3. Engineering properties of HSC

The aim of this section is to provide an overview of the structural engineering properties and characteristics of HSC, in light of the recent experimental and theoretical research and published results. There are other non-structural benefits of using HSC, for example the improved durability of the material which is a result of reduced porosity and the use of high-quality materials. However, the topic of durability is not discussed here in detail.

3.1. Compressive strength

Enhanced compressive strength is the most important of HSC's functional properties. Admixtures such as silica fume or fly ash are not essential to the manufacture of high-strength concrete with compressive strengths closer to 50 MPa. However, the incorporation of these mineral admixtures,

particularly silica fume does facilitate the process and silica fume is also essential to produce very high-strength concrete. The main reason for the spectacular increase in concrete strength in silica fume concrete is the creation of a dense concrete matrix enabled by the uniformly distributed fine silica fume particles in between larger cement particles. The use of superplasticizers and good compaction by vibration aids in the densification process lead to the higher strength. According to de Larrad and Malier [26], the microstructure of high-strength concrete is very dense and amorphous and contains very little free water. It has a very low-porosity and lacks the accumulation of lime crystals, as in the case of NSC.

3.2. Characteristic Principal Tensile strength

The tensile strength of HSC is significantly greater than that of NSC, though to a lesser extent than the compressive strength. Fracture surfaces are smooth, indicating the homogeneity of the material. The densification of the concrete matrix and the aggregate-matrix transition zone explains the improvement of the tensile strength.

The characteristic flexural tensile strength, f'_{cf} , and the characteristic principal tensile strength, f'_{ct} in accordance to various standard procedures are summarized in Table 2. The recommended values are plotted against f'_c in Figure 1.

Table 2: The characteristic flexural tensile strength (f'_{cf}) and the characteristic principal tensile strength (f'_{ct}) according to various standards

Standard	Recommendations for f'_{cf} and f'_{ct}
AS3600-2001 [27]	$f'_{cf} = 0.6\sqrt{f'_c}$ (1) $f'_{ct} = 0.4\sqrt{f'_c}$ (2)
AS3600-2009 [28]	$f'_{cf} = 0.6\sqrt{f'_c}$ (3) $f'_{ct} = 0.36\sqrt{f'_c}$ (4)
ACI 318-2005 [29] ACI 363R [30]	$f'_{cf} = 0.62\sqrt{f'_c}$ (5) $f'_{ct} = 0.59\sqrt{f'_c}$ (6)
Eurocode EC2-2004 [31]	$f'_{ct} = 2.12\ln\left[1 + \frac{f'_c + 8}{10}\right]$ (7) $f'_{cf} = \max [(1.6-h/1000)f'_{ct}; f'_{ct}]$ (8) Where h is the depth of the cross section

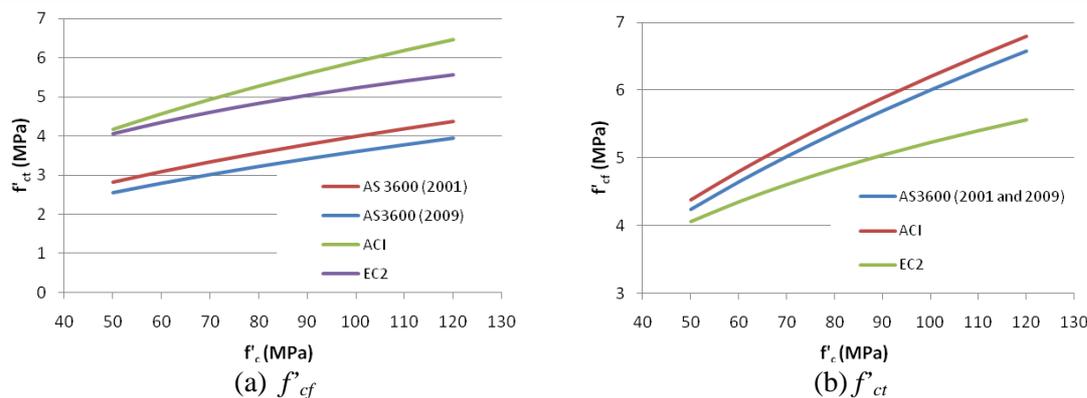


Fig.1: The characteristic flexural tensile strength (f'_{cf}) and the characteristic principal tensile strength (f'_{ct}) according to various standards

3.3. Modulus of Elasticity

The modulus of elasticity (E_c) of HSC is dependent on parameters such as the volume of aggregates, the modulus of the paste and the modulus of the aggregates. The recommendations for E_c values according to various standard procedures and researchers are summarized in Table 3 and plotted in Figure 2.

Setunge [32] has shown that the existing AS3600-2001 formula (Eq (9)) has the tendency to overestimate the elastic modulus of HSC. The new AS3600-2009 recommends Eq. (9) to estimate the modulus of elasticity of concrete up to 40 MPa. However, for concrete strength greater than 40 MPa, the new code recommends Eq. (10) to predict the elastic modulus of concrete.

Table 3: The modulus of elasticity according to various standards and researchers

Standard	Recommendations for E_c^*
AS3600-2001 [27]	$E_c = 0.043\rho^{1.5}\sqrt{f'_c} \pm 20\%$ (9)
AS3600-2009 [28]	$E_c = \rho^{1.5}(0.024\sqrt{f'_c} + 0.12) \pm 20\%$ (10)
ACI 318-2005 [29]	$E_c = (3.32\sqrt{f'_c} + 6895)\left(\frac{\rho}{2320}\right)^{1.5}$ (11)
Eurocode EC2-2004 [31]	$E_c = 22 \times 10^3 \left(\frac{f'_c}{10}\right)^{0.3}$ (12)
Mendis et al. [33]	$E_c = 0.43\eta\rho^{1.5}\sqrt{f'_c} \pm 20\%$ where, $\eta = 1.1 - 0.002f'_c \leq 1.0$, (13)
Carrasquillo et al. [32]	$E_c = (3320\sqrt{f'_c} + 6900)\left(\frac{\rho_c}{2320}\right)^{1.5}$ (14)

* The nominal density of normal weight HSC $\rho = 2400 \text{ kg/m}^3$

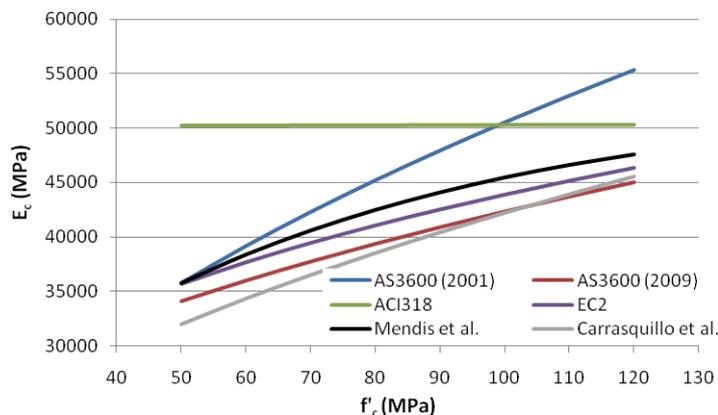


Fig. 2: Modulus of elasticity (E_c) values according to various standards and researcher

3.4. Required cover for durability

It is noted in the commentary of AS3600 that carbonation and ionisation (an increase in the reactive ion concentration such as chloride) are two factors that will influence durability in terms of corrosion of steel. HSC consists of a more uniform microstructure and lower porosity compared to NSC. This indicates a higher resistance to penetration of CO_2 and Cl ions into the concrete, thus reducing the corrosion of steel reinforcement. However, during production of HSC, macrocracking due to plastic shrinkage, microcracking due to self-dessication and thermal cracking may represent potential problems from a corrosion protection point of view. HSC's are also being specified for a range of critical civil engineering structures where the durability properties of the concrete are of paramount consideration and where design life requirements of over 100 years are needed. It is therefore prudent to also adopt the cover values specified in AS3600 for 50 MPa concrete for concrete strengths higher than 50 MPa. However the designers may reduce the cover values according to Table 4. It must be noted that for $f'_c < 70$ MPa, the same values as given in AS3600 [28] are recommended.

Table 4: Required Cover Values

Exposure Classification	Standard Formwork and Compaction are used (Table 4.10.3.2 of AS3600[28])		Rigid Formwork and Intense Compaction are used (Table 4.10.3.4 of AS3600[28])		Spun or Rolled Members (Table 4.10.3.5 of AS3600[28])	
	$f'_c < 70$ MPa	$f'_c \geq 70$ MPa	$f'_c < 70$ MPa	$f'_c \geq 70$ MPa	$f'_c < 70$ MPa	$f'_c \geq 70$ MPa
A1	20	20	15	15	10	10
A2	20	20	15	15	10	10
B1	25	20	20	15	15	10
B2	35	30	25	20	20	15
C	50	45	40	35	25	20

3.5. Fire resistance of HSC

Fire resistance of concrete members is normally accomplished by structural adequacy and insulation for a specified fire resistance period. Several researchers have concluded that with the exception of spalling, which is defined as the detachment of pieces of concrete when a concrete member is exposed to fire, there is no apparent reason to treat high-strength concrete differently from lower strength concrete.

Spalling can take place over the whole surface area of a member or in localised areas [38]. The risk of spalling is higher in high-strength concrete due to the following reasons:

- 1 Low permeability of HSC retains the moisture inside the concrete resulting in a high moisture content being present for prolonged periods.
- 2 Low porosity of HSC creates higher pore pressure.
- 3 HSC tends to be subject to higher compressive stresses than lower strength concrete.

In 1996, a comprehensive investigation was conducted at the National Institute of Standards and Technology, on experimental and analytical studies on fire performance of HSC. The key findings and a literature review are given by Phan [35]. It was observed that concrete with dense pastes resulting from the addition of silica fume are more susceptible to explosive spalling. HSC made with lightweight aggregate appears to be more prone to explosive spalling than HSC made of normal weight aggregate concretes. Chan et al. [36] showed that moisture content and strength are the two main factors governing explosive thermal spalling of concrete. Also, HSC specimens heated at higher heating rates, such as hydrocarbon fire which occurred in WTC collapse on September 11, and larger specimens are more prone to spalling than smaller specimens heated at lower rates.

According to the review by Phan [35], the material properties of HSC vary differently with temperature as compared to those of NSC. The differences are more pronounced in the temperature range of between 25°C to about 400°C, where higher strength concretes have higher rates of strength loss than lower strength concretes. These differences become less significant at temperatures above 400°C. Compressive strengths of HSC at 800°C decrease to about 30% of the original room temperature strengths. The tensile strength versus temperature relationships decreases similarly and almost linearly with temperature for HSC and NSC. HSC mixtures with silica fume have higher strength loss with increasing temperatures than HSC mixtures without silica fume.

There are only a few studies reported recently on the structural behaviour of HSC members subjected to fire. Meda et al. [37] studied the ultimate behaviour of HSC sections at high temperature and after cooling subjected to several fire durations. They concluded that HSC sections are more temperature-sensitive than NSC sections. However, the difference is not significant. Kodur [38] recommended design guidelines for mitigating spalling and enhancing fire endurance of HSC columns. In a recently concluded project at the University of Melbourne, Ta [39] found that HSC will go through more pronounced explosive spalling under hydro-carbon fire compared to standard fire.

4. Concluding Remarks

The constituents of HSC have been discussed. It is noted that the necessary ingredients making the concrete such as fly ash, slag and silica fume are mostly industrial byproducts which are otherwise wasted in landfills. This should be considered towards recognition of HSC as an environmentally friendly material. The main engineering properties of HSC are reviewed in the paper.

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